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Renewable hot dry rock geothermal energy source and its potential in Pakistan

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ABSTRACT

Geothermal energy source, one of the viable renewable energy sources, has encouraging potential to generate full base-load electricity, which has not been explored so far in Pakistan. Though the country can be benefited by harnessing the hydro-geothermal options of energy generation in areas where sources exist, but most of these sources lie in extreme remote and inaccessible rugged mountainous ranges away from the urban-industrial centers. On the other hand, the present study shows that the HDR geothermal option is one of the most viable renewable sources considering the tectonic setup of Pakistan. Results of the study highlight the HDR geothermal energy prospects at relatively deeper depths than hydro-geothermal resources in water-free condition. The basement tectonic analyses reveal that the HDR prospects could be found even just below the urban-industrial centers of Pakistan where there are no hot springs and/or geysers like southern Indus basin in Sindh province or the Kharan trough in the western Balochistan province. Presence of high earth-skin temperature gradient trends derived from satellite temperature data and the high geothermal gradient anomalous zone derived from scanty data of bottom-hole temperatures of some of the oil and gas exploratory wells, indicates encouraging prospects for HDR energy sources in southern Indus and Thar Desert regions inclusive of Karachi synclinorium area. These high geothermal gradients have been inferred to be the result of the deep-seated southern Indus and the Thar fossil-rift structures. Moreover, the prospects of the HDR geothermal energy sources have also been inferred in the Chagai Arc region and the Kharan–Panjgur tectonic depression in the western part of Pakistan based on the analysis of integrated geophysical data. If HDR prospects are developed, they can offer the sustainable, CO_2-free and independent of time, of day, of weather or season, and the base-load energy-generation resource.

Contents

1. Introduction

In proportion to the increasing trends of the world's population, urbanization and industrialization, the global demand for energy is increasing to the magnitude of extreme crisis particularly in the developing countries. It is anticipated that the conventional sources (particularly oil, gas, and coal) for the energy generation are not unlimited and at the present rate of consumption they would not last very long. Though, Pakistan derives more than 50% of its energy from natural gas, almost all of which is domestically produced, but still Pakistan is facing worst energy crisis due to high import dependence for the required crude oil and other petroleum

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products. The problem has been compounded by Pakistan's inability to increase its electricity-generating capacity through hydel, nuclear or other sources in the past decades, causing frequent rolling blackouts due to electricity shortages around the country. According to a research report of Tariq [1], Pakistan is expected to suffer energy crisis more in near future as some of the major natural gas reservoirs of the country will be exhausted during 2014–2025.

Efforts are continuously being made by public and private sectors to exploit the effective renewable energy-generation sources particularly the hydel, solar, wind and biomass. In addition to these renewable energy sources, the geothermal energy sources, which include thermal or electrical power produced from the heat contained in the Earth, should also be given due attention as they have not being considered on priority. Though, Pakistan has numerous surface manifestations of hydro-geothermal energy sources [2], but none of the sites has so far been developed for the direct utilization of the thermal energy or for the generation of electricity.

However, most of the easily located hydro-geothermal systems, those associated with the hot springs, geysers and fumaroles at the surface, are already known and many have been developed in several other countries. As of 2003, approximately 9000 MW of geothermal electrical generating capacity was present in more than 25 countries, mainly in the United States, Philippines, Mexico, Indonesia, Italy, Japan, New Zealand, Iceland, Costa Rica, El Salvador and Kenya [3,4], which represents about 0.25% of worldwide installed electrical generation capacity.

In fact, the use of hydro-geothermal energy is only a fraction of the total potential of geothermal energy, which mainly associated with the much deep-seated hot dry rocks (HDRs) generally at depths ranging around 4–6 km. Based on some presumed parameters, the geothermal energy potential in the uppermost 10 km of the Earth's crust was tentatively estimated to 50,000 times the energy of all known oil and gas resources in the world [5]. In general, these resources were not considered technologically or economically accessible [6], but now it is not so considering the on-going research and development activities for the exploration of deep HDR sources and cost-effective development of HDR geothermal energy exploitation technologies, i.e., enhanced geothermal systems (EGS) in countries like Australia, Germany, USA, etc.

As with any development of new technology, some aspects of the new technology have been accepted by the general public, but some have not yet been accepted and await further clarification before such acceptance is possible. Same is the case for the adoption of HDR geothermal energy technology in developing countries like Pakistan.

Considering the geodynamic scenario [7–9], the enormous HDR geothermal energy potential is expected to exist associated with the deep-seated basement structures in Pakistan. This paper describes an overview of the "hot dry rocks" as the exploitable renewable geothermal energy source and its potential in Pakistan for the development of the electric power generation options in areas close to major urban-industrial centers.

2. HDR geothermal energy

Tough, it looks simple that the HDR geothermal energy is the energy derived from the heat of the earth's core, but there are distinct variations in the distribution patterns of the geothermal heat-flow associated with the varying tectonic activities within the earth's lithosphere. The fact is that the understanding of the plate tectonic processes plays important role for any area to identify the geothermal HDR energy targets.There are two basic types of geothermal energy—one type that is available from subsurface hydrothermal systems at relatively shallower depths down to about 2–3 km or even shallower depth, i.e., hot geo-fluids as manifested in form of hot springs, geysers, etc. at the surface. The plate tectonics processes cause high temperatures enough to melt rock forming magma, which moves up toward the earth's crust and carries heat from below. Sometimes magma rises to the surface through thin or fractured crust as lava. Generally, most magma remains below earth's surface and heats the surrounding rocks and subterranean water. Some of this water comes all the way up to the surface through faults and fractures in the earth as hot springs or geysers. When this rising hot water and steam is trapped in permeable rocks under a layer of impermeable rocks, it is called a hydro-geothermal reservoir. These reservoirs are the sources of hydro-geothermal energy that can potentially be tapped for electricity generation or direct use [4]. Some preliminary studies have been carried out only for the identification of the hydro-geothermal sources in Pakistan [10–12], which have been integrated and reviewed [13]. But no site has so far been fully explored and/or exploited to generate electricity in Pakistan.The other type of geothermal energy is sourced from hot dry rocks (HDRs) that is overlaid by thick cover of sedimentary rock sequences relatively much below the hydro-geothermal systems in water-free deep-seated environment at depths ranging from 4 to 6 km. Geothermal energy from hot rocks differs from the conventional hydrothermal energy process that produces power commercially in geologically active areas. HDR energy is clean, abundant, and reliable and if properly developed, it can offer a renewable, sustainable, CO_2-free and independent of time of day, of weather or season full base-load energy sources.

Enhanced geothermal systems (EGS) have been developed to extract energy from HDR sources by pumping water down through the injection well to hot basement rocks, which are made rich by hydraulic fracturing causing enhanced secondary porosity and permeability. In fact, the enhanced secondary porosity and permeability provide a connection between injection and withdrawal wells to develop a closed water-circulation system for extracting and transferring heat from hot rocks at depth to the surface. The extracted hot fluids are used at the surface for generating electricity. In general, the temperatures for hot water and steam range from 120 to 370 °C for electricity generation.

The future promising new HDR geothermal technology is designed to be able to tap into much deeper geothermal resources than current technologies permit. Moreover, the HDR geothermal technology is expected to provide geothermal energy to be used for low cost, renewable electricity generation anywhere in the world not only restricted to hot spring or geyser areas as being attempted in Australia [14]. No work is so far done to identify the HDR source potentials in Pakistan.

3. Tectonic domains and prospects for hot dry rocks

Western margin of the Indo-Pakistan continental plate hosts the past collisional tectonic mega-thrust boundaries in the northern part and the extensional tectonics resulting in rifted protocontinent and new oceanic crust created during sea-floor spreading [15,16,9]. The eastern part of Pakistan, i.e., the region comprising mainly of Indus Plains, is characterized by a broad north-south—trending sedimentary basin having thick tertiary sequences underlain by Mesozoic and older rocks and overlain by quaternary floodplain sediment deposits of the Indus River (Fig. 1). Indus basin is bounded by a desertic ecosystem on the east and by mountainous region of fold and thrust belts in Pakistan on the west. Intensity of tertiary folding increases westward and becomes more pronounced in the strongly folded and faulted areas of the axial fold and thrust belts.

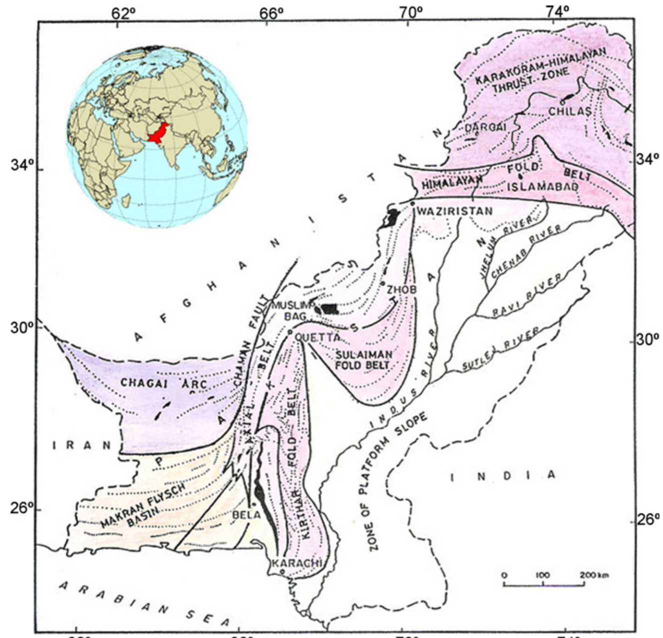

Fig. 1. Map shows index map of Pakistan and the salient tectonic features (modified after Zaigham [9]).

The basement manifestations were only known as the "highs" of Jaccobabad, Khairpur, Hyderabad, and others [17] and no plausible explanation could be established till early 1990s, largely owing to the lack of subsurface geological and geophysical information. Most of the earlier workers considered these highs as the result of subsurface northwest trending, narrow, fingerlike extensions of the Indian shield, known as "re-entrances," which caused deformation of the overlying geological strata [18]. But during early 1990s, a north-south trending southern Indus fossil-failed rift structure was identified, based on the detailed analysis of the archive aeromagnetic data, buried beneath the thick piles of the Mesozoic and Cenozoic sediments in the southern Indus basin [9,19]. The depths of these inferred rift segments (i.e., the horsts and grabens) were estimated as ± 5 km for southern, ± 9 km for central, and ± 7 km for northern. It was inferred that the vertical displacements of these horsts and grabens have affected the overlying sediments reflecting as surface manifestations, which were used to call as Sibi, Jacobabad, Khairpur, Hydrabad and other "highs".

As evident from the fact that the rifting-tectonic environment encourages the high-heat flow to the upper crust from the interior of the earth, the schematic tectonic model of southern Indus fossil-failed rift (Fig. 2) shows the significant prospects for the development of relatively higher geothermal anomalies within the basin.

Similarly, in the southeast of the Indus-failed rift, another fossil-failed rift was also identified as Thar rift (Fig. 3) based on analysis and modeling of the seismic data [20,8]. These rift structures illustrate excellent environments for the presence of HDR sources buried under the sufficiently thick sedimentary rock sequences. Such tectonic conditions indicate the presence of potentially high-heat generating granitic basements and maximum horizontal stress orientations that are favorable for developing horizontally oriented high-temperature geothermal reservoirs.

Western part of Pakistan shows dominance of subduction tectonics [21]. Significant prospects of encouraging HDR geothermal energy sources have also been inferred in the Chagai fossil-volcanic-arc region and the Kharan–Panjgur tectonic depression based on the analyses of aeromagnetic and ground-magnetic and ground-gravity and satellite-gravity anomalies, seismicity and geological data [7,22]. Hisamuddin [7] modified the western Pakistan subduction model of [22], which has been further modified in relevance to HDR geothermal study (Fig. 4a). The development of extensional/rift basin at the front of the accretionary wedge and the volcanic arc is inferred to cause the migration of Chagai volcanic arc and up-rising of magma to generate new high-heat generating granitic basement beneath the relatively thick flysch sediments of the Panjgur–Kharan trough as exploitable HDR geothermal target. This 'high-heat generating granitic basement' is presently inferred to manifest the reduced-magnetic anomaly over an area within south Mashkel trough (Fig. 4b). It is expected that the required HDR target may encounter at much shallower depth in Kharan–Panjgur trough as compared to that of the Indus basin.

4. Pattern of geothermal heat-flow

For the exploitation of geothermal energy into power, the most crucial task is to locate high-heat granetic bodies at as shallowest depths as possible, which generally, encounter down to the depths ranging from 3 to 7 km. Moreover, the precise knowledge of physical and chemical characteristics of the deep-seated HDR targets is also imperative for the economically feasible development. For example, sufficient porosity and fracture permeability are the primary parameters to produce large quantities of thermal water, either naturally or by enhanced geothermal system technologies, which need to be evaluated. Similarly, an understanding of relative stress magnitudes is required for assessing the uncertainty in the application of HDR technology, which are also to be best known for the working basin. Likewise, the geochemical analyses of basement rocks are required to assess the heat-generation capacity of rocks because in case of small differences in concentrations of the thorium and uranium can have quite significant impacts on heat-generation capacity, whereas large variations in potassium concentration have only a second-order effect on the heat-generation capacity.

In general, the geological, hydro-geological, electrical, gravity and magnetic, geochemical, and seismic data are used to locate the potential geothermal resources before the exploratory drilling. Exploration for geothermal energy has some similarities to petroleum exploration, but with certain key differences [23], such as high-temperature logging and reservoir stimulation.

In view to assess the geothermal heat-flow trends in different parts of Pakistan, two types of data sets have been adopted for the present study, i.e., the satellite earth-skin temperatures in Pakistan and the available thermal gradient data of a few exploratory wells drilled for the investigation of oil and gas in Indus basin of Pakistan.

4.1. Trends of thin-skin surface temperatures

The earth's heat conductivity is so low that only a minute fraction of the solar heat penetrates very far into the earth. The effects of solar radiation, energy released by earthquakes, and tidal friction on the interior of the earth are negligible in comparison with released by tectonic processes in the earth's interior [24]. Considering the domination of heat-flow from interior of earth towards outer crust, 22 years (July 1983 to June 2005) satellite recorded temperature data of the earth-skin are acquired from the Surface Meteorology and Solar Energy (SSE) Section of Applied Science Program, Earth-Sun System Division, Science Mission Directorate, National Aeronautics and Space Administrations (NASA) [25].

About 200 nodal data points of earth-skin 22 years average annual temperatures have been processed and a preliminary regional map of the earth-skin thermal gradient (EST) trend has

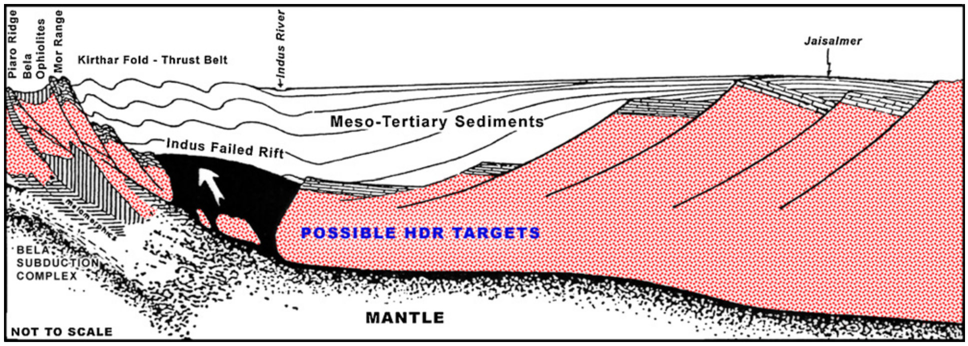

Fig. 2. Schematic fossil-failed rift model illustrates the present-day tectonic setting in the southern Indus basin. The basement mass shows the presence of high-heated dry granitic bodies beneath the thick pile of Mesozoic–tertiary sedimentary sequences (modified after Zaigham [9]).

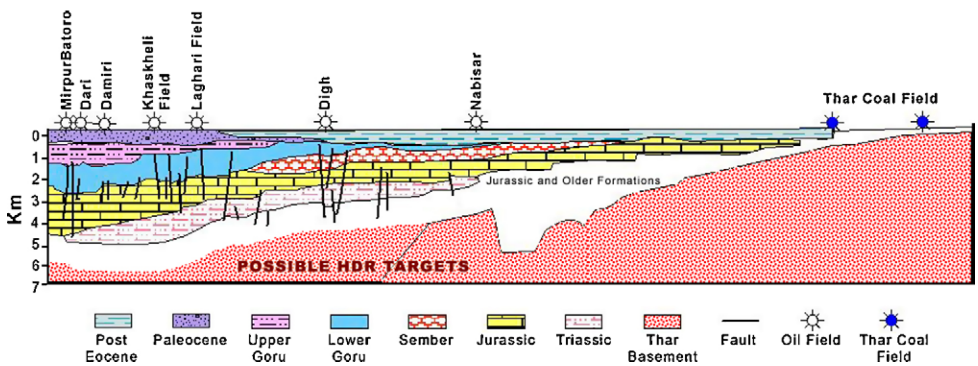

Fig. 3. Geologic structural cross-section of Thar rifted monocline across southern part of Indus basin and Thar Desert. On the eastern side, the granitic basement is exposed at places on the surface, but westward it is deepening beneath the Mesozoic–tertiary sedimentary sequences and the older rocks. Basement deepening corresponds to westward increase in geothermal gradient as revealed from borehole–bottom temperatures that indicate good prospects for HDR at depth of 5–6 km.

been generated (Fig. 5) by using the regular spline interpolation method of GIS technique.

Strong EST gradient trend is mainly observed in the south-eastern part of Pakistan comprising of the Karachi, Uthal, Dadu, Hydrabad, Islamkot and coastal areas, which ranges from 28 to 31 °C. The high EST gradient trend is decreasing in intensity towards northeast upto Faisalabad area and westward along coastal belt further extending into Iran that ranges from 26 to 28 °C. The northern part of the western Pakistan, i.e., Panjgur, Kharan and Chagai areas, is dominated by the moderate EST trend

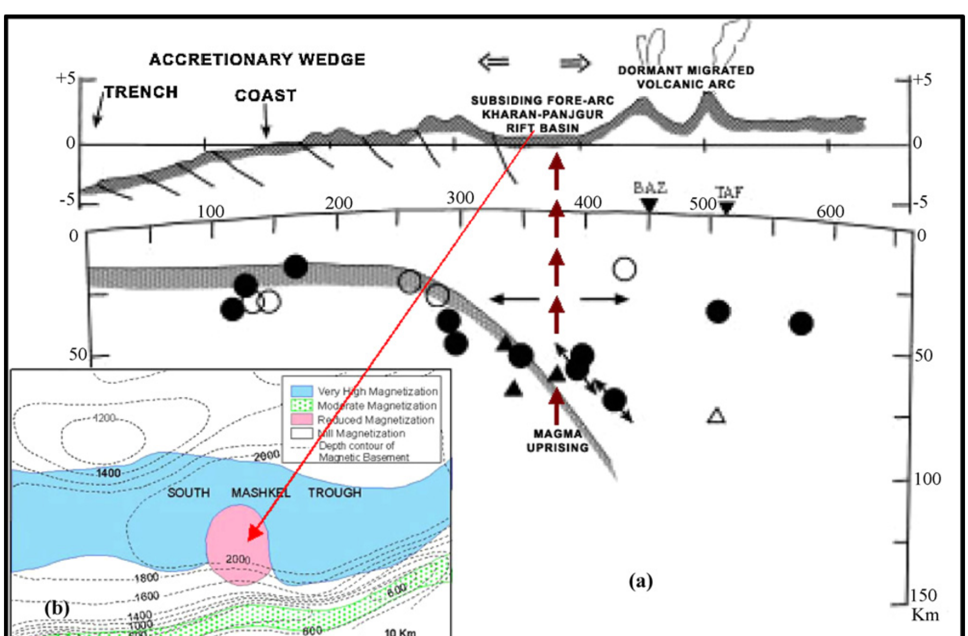

Fig. 4. Subduction model of western part of Pakistan. (a) Model shows rifting at the front edge of accretionary wedge and the Chagai volcanic arc causing upward heat-flow from the subducting oceanic plate. (b) Deep-seated basement body showing reduced magnetization is inferred to be a good target as HDR source.

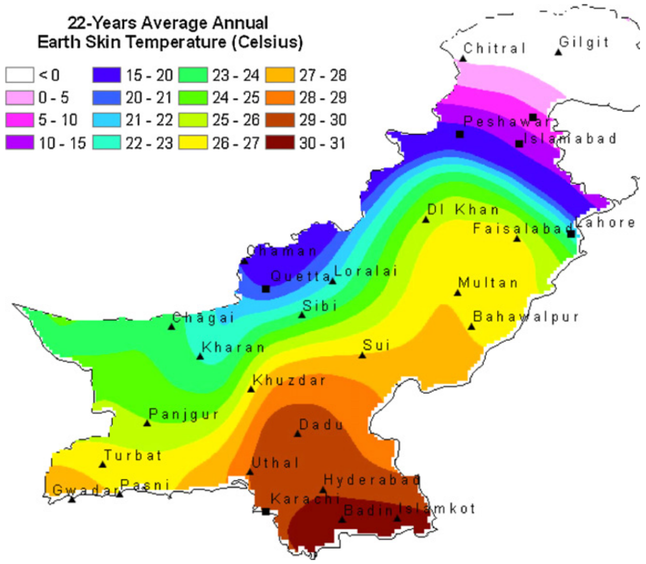

Fig. 5. Map shows the 22 years average annual earth-skin temperature gradient trends in Pakistan as derived from satellite earth-skin temperature data taken from NASA.

ranging from 21 to 26 °C. This trend extends eastward in a narrow zone enveloping the moderate EST trend passing across of Sibi, Laralai, D.I. Khan and Lahore. Northern and the northwestern part of Pakistan show the low EST trends in Quetta, Chaman, Peshawar, Islamabad, Chitral and Gilgit areas.

Comparing the barrenness of the western and southeastern regions, the western desertic region comprising of Chagai volcanic arc and the Makran flysch basin, where vegetation, agricultural activity and annual rains are rare and the solar radiations are high, but the EST trend is moderate as compared to the high EST trend of the southeastern region comprising of mainly s of southern Indus basin and the southeastern part of the Kirthar mountain ranges with good vegetation, agricultural activities, network of river and canals and high annual rainfall trends. Thus, it is inferred that the EST trends are being controlled by the subsurface active tectonic processes rather than solar radiation in both the regions particularly.

On the basis of the EST trends, Pakistan can apparently be divided into three priority areas for the exploration of HDR geothermal resources. The southeastern area of strong EST gradient ranging from 31 to 26 °C, the areas of moderate EST gradient ranging from 21 to 26 °C and the areas of low EST gradients below 20 °C may be taken as priority I, II, and III respectively for the detailed HDR investigations.

4.2. Geothermal gradients of Indus basin

In view of the complex tectonic setup, considerable variations are expected in the lateral and vertical geothermal gradient trends in and around the Indus basin. For the present study, scanty borehole-bottom temperatures data of some of the exploratory oil and gas wells have been acquired from unpublished and published literature [11,12,26] to develop a geothermal gradient anomaly map of Indus basin. The thermal gradient data of 60 exploratory oil and gas wells have been processed and a preliminary regional anomaly map of the geothermal gradient has been generated (Fig. 6) by using the inverse distance weighted (IDW) interpolation method of GIS technique.

The results of present study show interesting anomalous conditions revealing new relatively deeper HDR geothermal source potentials in the flood-plain regions of the Indus basin. The 3 °C/100 m geothermal gradient shows the background value of the

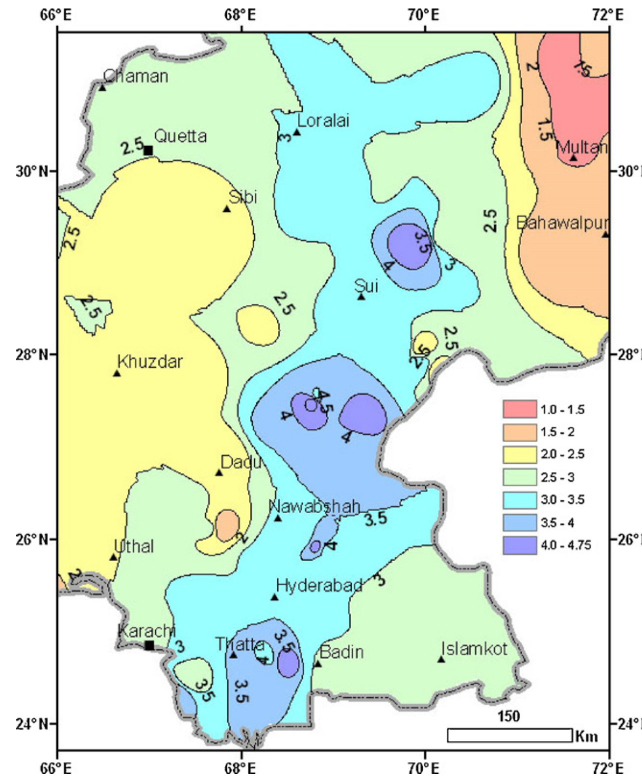

Fig. 6. Map shows preliminary regional geothermal gradient anomalies derived from borehole thermal gradients of about 60 exploratory oil and gas wells drilled in Indus basin.

high geothermal anomalous zone passing northward in NNE direction from coastal area in the south association with the exposed geological trends following the eastern part of the axial fold–thrust belt.

In the south, this zone stretches between Karachi and Badin and approaches more or less with the same width up to east of Sibi and west of Bhawalpur. The zone shows three main geothermal anomalous groups of geothermal gradient anomalies having higher values of 4 and/or 4.5 °C/100 m.

The southern high geothermal gradient anomalies between Karachi and Badin are inferred to be associated with faulted segments of the Thar fossil-failed rift. The mid-zone and the northern higher geothermal anomalies northeast of Nawabshah and Sui, respectively, show their association with the faulted segments of the Indus basin fossil-failed rift. Quadri and Shuaib [26] also reported that the thermal gradients increase from east (2.36 °C/100 m) to west (4.3 °C/100 m) in the Badin–Hydrabad area based on the bottom-hole temperatures of some of the wells that supports the present study.

5. Discussion

Though, the results of the present study show encouraging prospects for the availability of HDR geothermal resources, but preliminary research work is not sufficient for the relevant technological development. There is a great need to establish a comprehensive geoscientific database relevant to different HDR geothermal exploratory disciplines, because in the absence of adequate database the extent and economic feasibility of HDR geothermal resource development technology cannot be achieve for Pakistan.

Anticipating the future energy crises, the HDR resources need seriously to be studied for their commercial development in

Pakistan. The fact is that to explore the HDR geotechnical characteristics, required to assess the suitability of installation of the sustainable "enhanced geothermal system", the deep boreholes need to be drilled as the HDR resources are much deeper than the hydrothermal resources. The costs of such well increase exponentially with depth, and thus they look much more expensive at the initial introductory phase of the technology development. In case of Pakistan, such costs could be saved by using the subsurface information acquired from the exploratory and development oil and gas drilled wells.

In this connection as the first step, a comprehensive research-cum-professional work must be taken up on priority-basis for the data gathering, validating, interpreting and modeling of the already existed enormous data of the exploratory & development wells drilled for the development of oil and gas sector in Pakistan.

Since 1868 till July 2007, a total of 1567 exploratory (689) and development (878) wells cover the vast regions in the Indus basin, Potwar Plateau, eastern flank of the axial fold–thrust belt, coastal zone of the Arabian Sea [27]. More than 450 exploratory wells have been abandoned, which account for an enormous investment of the petroleum industry.

The archive data lying in the record-files may play a vital role for the development of the HDR geothermal energy for the generation of the electricity in the country. If the archive data, relevant to the proposed research study for the identification of deep-seated HDR resources, is allowed and utilized, then the initial exploration cost and time will be saved considerably minimizing the capital cost of the HDR exploration project. Thus, a substantial cost invested on the abandoned wells would also be cashed back indirectly.

6. Conclusions

The results of the present study shows that the surface geological setup and the deep-seated basement tectonic features indicate bright prospect for development of HDR geothermal energy resources to generate electricity and/or direct heat in Pakistan particularly in areas close to the main urban and/or industrial centers where there are no hot springs and/or geysers exist.

The earth-skin temperature gradient trends derived from satellite data and the thermal gradient anomalies derived from borehole–bottom temperatures of a few oil and gas exploratory wells show good potentials for presence of HDR geothermal targets associated with the Indus and Thar fossil-failed rifts, and Panjgur–Kharan extensional trough in convergent tectonic domain.

There is a great need to establish a comprehensive geoscientific database relevant to different HDR geothermal exploratory disciplines, because in the absence of adequate database the extent and economic feasibility of HDR geothermal resource development technology cannot be achieve for Pakistan.

The archive data of exploratory and development oil and gas wells lying in the record-files may play a vital role to identify the HDR targets and to explore the HDR geotechnical characteristics required to assess the suitability of installation of the sustainable "enhanced geothermal system".

References

[1] Tariq N. Energy crisis of Pakistan. Report of Jang development reporting cell: the Daily Jang Karachi. September 9, 2004.
[2] Zaigham NA, Nayyar ZA. Prospects of renewable energy sources in Pakistan. In: Khan HA, Qurashi MM, Hussain T, Hayee I, editors. Renewable energy technologies and sustainable development. Pakistan: COMSATS; 2005. p. 65–86.
[3] Dickson MH, Fanelh M. What is geothermal energy? [online]. http://www.geothermal-energy.org/geo/geoenergy.php; 2004.
[4] Shibaki M, Beck F. Geothermal energy for electric power—a REPP Issue Brief [online]. http://www.repp.org/articles/static/1/binaries/Geothermal_Issue_Brief.pdf; 2003.
[5] USD/EO/EERE. U.S. Department of Energy Office of Energy Efficiency and Renewable Energy [online]. http://www.eren.doe.gov/state_energy/technology_overview.cfm?techid=5, 2002.
[6] GEA. Geothermal electric production potential, based upon US Geologic Survey Testimony before the Subcommittee on Energy and Mineral Resources of the House Resources Committee [online]. http://www.geo-energy.org/UsResources.htm; 2001.
[7] Hisamuddin N. Tectonic interrelationship between Khuzdar region and submarine Arabian sea structures and their economic potentials. Ph.D. thesis, Karachi: University of Karachi; 2004.
[8] Zaigham NA, Hisamuddin N, Ahmed M. Thar-rift and its significance for hydrocarbon. Special Publication of Society of Petroleum Engineers and Pakistan Association of Petroleum Geologists. Islamabad: Orient Petroleum Inc.; 2000. pp. 117–130.
[9] Zaigham NA. Bela ophiolites and associated minealizations in southern part of axial-belt of Pakistan. Ph.D. thesis, Karachi: University of Karachi; 1991.
[10] Todaka N, Shuja TA, Jamiluddin S, Khan NA, Pasha MA, Iqbal MA. Preliminary study of geothermal energy resources of Pakistan. GSP I.R.407; 1999. p. 93.
[11] Kazmi AH, Jan MQ. Geology and tectonics of Pakistan, Karachi. Islamabad: Graphic Publishers; 1997. pp. 490–500.
[12] Khan MA, Raza HA. The role of geothermal gradients in hydrocarbon on Pakistan. J Petrol Geol 1986;9(3):245–58.
[13] Zaigham NA, Nayyar ZA, Hisamuddin N. Review of geothermal energy resources in Pakistan. Renew Sustain Energy Rev 2009;13(1):223–32.
[14] Ghori H. Western Australia's geothermal resources. In: Proceedings of the AAPG Annual Convention; 2008.
[15] Powell CMA. Speculative tectonic history of Pakistan and surroundings—some constraints from the Indian ocean. In: Farah A, DeJong KA, editors. Geodynamics of Pakistan. Quetta: Geological Survey of Pakistan; 1979. p. 5–24.
[16] Biswas SK. Rift basins in western margin of India and their hydrocarbon prospects with special reference to Kutch basin. AAPG Bull 1982;66:1497–513.
[17] Kazmi AH, Rana RA. Tectonic map of Pakistan. Quetta: Geological Survey of Pakistan; 1982.
[18] Wadia DN. The syntaxis of the northwest Himalaya, its rocks, tectonics and orogeny. Geol Surv India Rec 1931;65:189–220.
[19] Zaigham NA, Mallick KA. Prospect of hydrocarbons associated with the fossil rift structures of southern Indus basin, Pakistan. AAPG Bull 2000;84(11):1833–48.
[20] Zaigham NA, Ahmed A. Seimo-stratigraphy and basement configuration in relation to coal bearing horizons in the Thar Parkar Desert, Sindh Province, Pakistan. GSP Rec 1993;100.
[21] Zaigham NA, Ahmed M. A segment subduction of Arabian oceanic plate verses western margin of Indo-Pakistan subcontinental plate. Ofioliti 2000 2000;25(2):67–73.
[22] Jacob KH, Quittemeyer RC. The Makran region of Pakistan and Iran; arahtrench arc system with active plate subduction. In: Farah A, DeJong KA, editors. Geodynamics of Pakistan. Quetta: Geological Survey of Pakistan; 1979 p. 305–18.
[23] Narayan SP, Naseby D, Yang Z, Rahman SS. Creation of HDR reservoirs under Australian in-situ stress conditions. In: Proceedings of the Twenty-third Workshop on Geothermal Reservoir Engineering. CA, USA: Stanford University; 1998. p. 322–9.
[24] Sheriff RE. Geophysical methods. New Jersey: Prentice Hall; 1989.
[25] Stackhouse PW, Whillock CH. Surface meteorology and solar energy [online]. http://eosweb.lasc.nasa.gov/sse/; 2006.
[26] Quadri VN, Shuaib M. Hydrocarbon prospects of southern Indus basin. AAPG Bull 1986;70:730–47.
[27] HDIP. Pakistan energy yearbook 2007. Islamabad: Hydrocarbon Development Institute of Pakistan; 2008.